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A NAVAL TASK FORCE PERFORMANCE ASSESSMENT METHODOLOGY

CARL M. BENNETT

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13. ABSTRACT *(Maximum 200 words)*
A manageable and practical Naval Task Force performance assessment methodology is presented. The methodology is based on Multiple Attribute Decision Making [MADM] theory in general and the Analytic Hierarchy Process [AHP] in particular. The utility of the methodology in the development of an expert panel assessment and ranking of Naval Task Force architectural options [physical implementation options] with respect to a standardized Naval Task Force functional performance specification is suggested.

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INTRODUCTION

BACKGROUND

A requirement exists for a practical Naval Task Force performance assessment methodology for evaluating and rank ordering Naval Task Force architectural options in terms of overall mission performance. The desired properties of such a methodology are effectiveness, timeliness, affordability, traceability, repeatability and understandability. Past performance assessment methodologies, even when effective, have not provided assessments that were timely, affordable, traceable, repeatable or understandable.

A Naval Task Force is a very complex system. A practical Naval Task Force performance assessment methodology will likely be complex as well. However, complexity can often be understood by placing the assessment problem in a logical framework composed of understandable components based on fleet oriented cognitive perceptions.

A significant contribution to the development of a Naval Task Force performance assessment methodology was the formulation of Mission Success Criteria (MSC), and fleet oriented Force Performance Metrics (FPM) for the Top Level Warfare Requirements (TLWR) process by the Applied Physics Laboratory, the Naval Surface Weapons Center, and others circa 1985-87. The FPM are: Battle Space, Battle Management, Fire Power, Countermeasures, Sustainability, Survivability, Mobility, and Readiness. There are three types of MSC: Mission Objectives Accomplishments, Capital Resource Losses, and Expendable Resources Consumed. The FPM are useful in describing force architectural options and can be conceptually linked to scenario dependent MSC.

An additional contribution to development of a Naval Task Force performance assessment methodology was the development, at the Naval Coastal Systems Center [1], of a methodology for explicitly defining Naval Task Force functional performance. The methodology is based on a computerized, structured breakdown of Task Force functional performance together with an explicit identification of all functional interfaces. This Computer Aided Systems Engineering (CASE) tool based methodology could serve as a framework for a computerized standard presentation of a Naval Task Force architectural option (physical implementation option) for performing the required Naval Task Force functions. Quantification of the performance of a given physical option with respect to required functional performance can then be evaluated and analytically related to FPM.

A relationship between the performance of a given Naval Task Force architectural option and the FPM, and the FPM and the MSC of a given mission scenario, can be generally obtained through the exercise of a performance assessment methodology.

PURPOSE

The purpose of the paper is to present a practical methodology for use in evaluating and ranking Naval Task Force architectural options. The proposed methodology is generally based on Multiple Attribute Decision Making (MADM) [2]. The methodology is presented in the context of the overall Task Force assessment process defined below.

A TASK FORCE ASSESSMENT PROCESS

The Task Force performance analysis methodology presented is seen as applicable to Phase-3 of the four phase Task Force assessment process of Figure 1. The Naval Task Force functional performance generation methodology developed by Bennett [1] is seen as

applicable to Phases 1 and 2. Phase-4 involves a benefits to cost-risk analysis, a final Naval Task Force architectural option(s) selection process, and documentation of the results. Assessment process details are shown in Appendix B Figures B1 through B4.

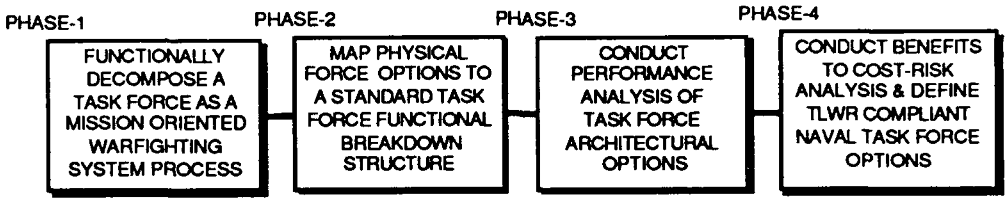

FIGURE 1. A NAVAL TASK FORCE ARCHITECTURE ASSESSMENT PROCESS

A TASK FORCE PERFORMANCE ANALYSIS

After careful consideration of the numerous MADM methodologies, the Analytic Hierarchy Process (AHP) of Thomas L. Saaty [3] has been selected as the methodology for defining a practical Naval Task Force performance analysis for Phase-3 of an assessment process. The context of the AHP in the array of available MADM methodologies is presented in Appendix A, along with related mathematical techniques, etc. The following presentation makes no mathematical demands on the reader. Required elements of Appendix A will be evoked by reference where needed.

Saaty [3] outlines explicit steps for the conduct of an AHP analysis using groups of decision makers (expert panels). A specific AHP formulation for a proposed Naval Task Force Performance analysis plan using Saaty's steps follows.

The first step is to define the problem and specify *the nature of the desired solution.* The problem posed is: Select the "best" physical implementation option (**alternative**) for a Naval Task Force functional architecture from among several explicitly defined **alternatives**. "Best" is specified as the **alternative** with the highest "overall" mission effectiveness among the **alternatives.** "Overall" is defined as the aggregate mission effectiveness taken over a set of potential mission scenarios.

The second step is to develop and structure an AHP hierarchy from a top level overall Naval Force procurement point of view down to a level at which procurement of physical components comprising a set of Naval Task Force architectural options or **physical options / alternatives** can be explicitly considered in a procurement process.

Proposed AHP hierarchy levels are described as follows:

Level "0", the top level, consists of a single **attribute**, Task Force Mission Effectiveness, derived from the results of Step-1.

Levels "1" consists of Regional War, and Global War.

Level "2" consists of Sea Control, Power Projection, and Sealift/SLOC Protection. Note that Levels "1" and "2" combine to delineate a set of six generic mission scenarios, i.e. Sea Control in a Regional War, Power Projection in a Regional War, Sealift/SLOC Protection in a Regional War, Sea Control in a Global War, Power Projection in a Global War, and Sealift/SLOC Protection in a Global War.

Level "3" is comprised of the Force Performance Metrics (FPM), i.e. Battle Space, Battle Management, Fire Power, Countermeasures, Sustainability, Survivability, Mobility, and Readiness.

Level "4" is comprised of the current Naval Warfare Tasks supplemented by Anti Space Warfare (ASPW) and Radio and Electronic Combat (R&EC). The current Naval Warfare Tasks are of two classes, fundamental tasks and supporting tasks. The fundamental tasks are anti-air warfare (AAW), anti-submarine warfare (ASW), anti-surface warfare (ASUW), strike warfare (STW), amphibious warfare (AMW), and mine warfare (MIW). The supporting tasks are special warfare (NSW), ocean surveillance (SURV), intelligence (INTEL), command, control and communications (C3), electronic warfare (EW), and logistics (LOG). Note that rational clusters of the Naval Warfare Tasks might be considered to simplify this level.

Level "5" is derived from observing the utility of a generic set of "lower" level functional decomposition **attributes** in previous Warfare Task functional decompositions [1, 4], i.e. Receive, Sense, Plan, Observe, Assess, Execute, Issue, and Act. Appendix C includes definitions of these generic fundamental or primitive functions. Level "5" is comprised of a set of eight fundamental or primitive functions for each Naval Warfare Task considered. If clusters of Naval Warfare Tasks are considered, there would only be one set of eight fundamental or primitive functions for each cluster considered. Thus clustering would simplify this level as well.

Level "6", the bottom level is comprised of the **physical options / alternatives** to be evaluated using the proposed AHP hierarchy.

Figure 2 is a diagram of the proposed hierarchy.

A proposed structural mappings between levels of the hierarchy are shown in Figures 3-5. Figure 3 indicates the proposed hierarchical structure for levels "0" through "3" . This portion of the hierarchy is composed entirely of **attributes** of a functional nature, and is thus "functional" as defined and required by the AHP . The hierarchy is also "complete", as defined by the AHP, since all **attributes** at a given level connect to every **attribute** at the next higher level [3]. This hierarchical structure defines an explicit linear mathematical relationship between the FPM and the MSC effectiveness criterion. The nature of this Hierarchcial Additive Weighting (HAW) relationship is discussed in Appendix A. The procedure for analytically obtaining the relative importance (weighting) of an **attribute** at a given level with respect to an **attribute** at the next higher level is addressed in later steps. Appendix A provides the necessary mathematical details.

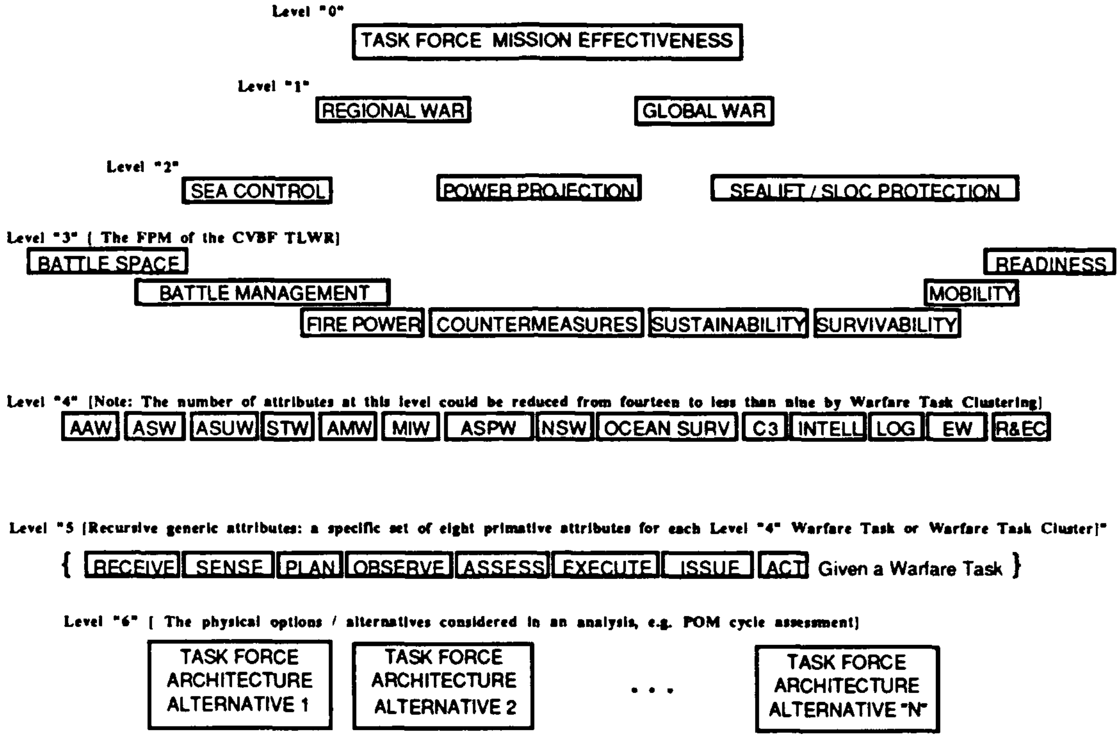

FIGURE 2: A NAVAL TASK FORCE ASSESSMENT HIERARCHY

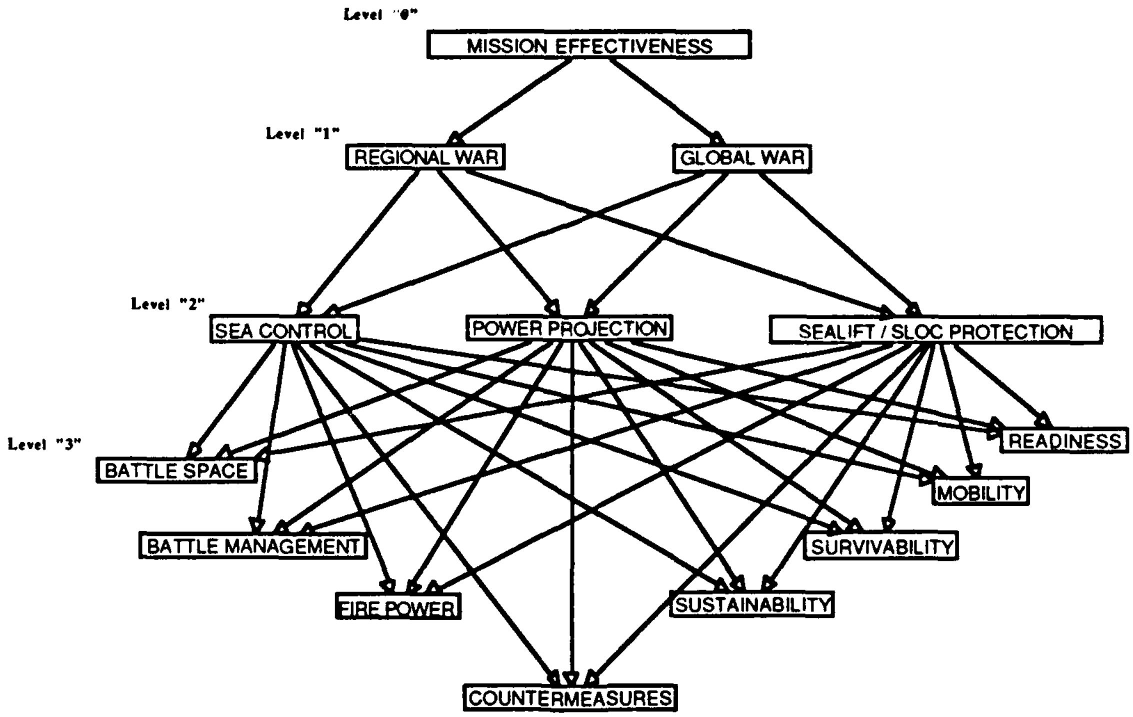

FIGURE 3. TASK FORCE HIERARCHY LEVELS "0" THROUGH "3"

Representative sub-structure mappings for the remaining hierarchical levels are shown in Figures 4 and 5.

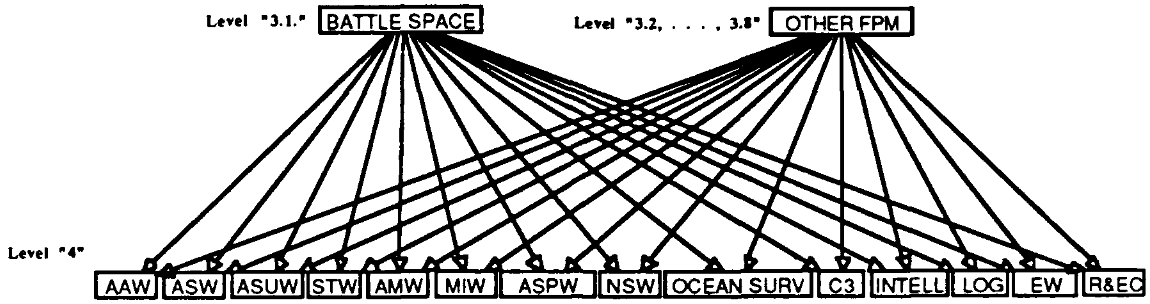

FIGURE 4. TASK FORCE HIERARCHY LEVELS "3.1" [BATTLE SPACE] TO LEVEL "4"

The hierarchical structure in Figure 4 maps Battle Space to Level "4". The mapping structures for the other seven (7) Level "3" FPM **attributes** to Level "4" **attributes** are identical to the structure for Battle Space shown in Figure 4. Thus the Level "3" to Level "4" hierarchical structure is both "functional" and "complete" as defined by the AHP.

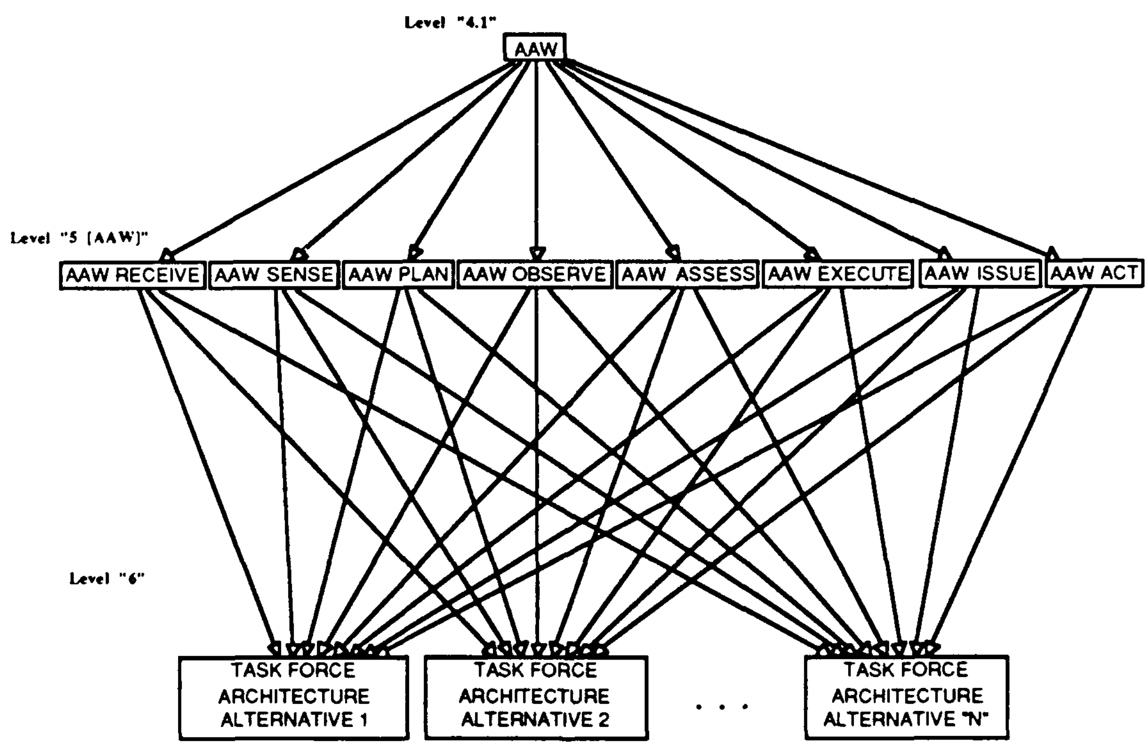

FIGURE 5. TASK FORCE HIERARCHY LEVELS "4.1" [AAW] TO LEVEL "6"

The Level "4" to Level "5" hierarchical structure is "functional" but not "complete" . It is not "complete" because the eight (8) Level "5" **attributes** specifically related to AAW in Figure 5 do not map to the other thirteen (13) Level "4" Warfare Task **attributes**, e.g. ASW, MIW, LOG, etc. The structures for the other thirteen (13) Level "4' Warfare Task **attributes** to their related eight (8) Warfare Task specific Level "5" **attributes** are similar to the structure for AAW in Figure 5, and are also "functional" but not "complete" , e.g. ASW is not mapped to MIW Plan, etc. Thus the level "4" to Level

"5" hierarchical structure is "functional" but not "complete" . Note, there is a total of eight times fourteen (8x14) or one-hundred twelve (112) Level "5" **attributes** ranging from AAW Receive to R&EC Act.

The cross Warfare Task types of mapping relationships are omitted from the structure by design to reduce the scope and magnitude of the AHP analyses. The omitted mappings could be added if time and resources permit. However, such an AHP hierarchy enhancement may not be worth the added effort, as will be seen in step 3.

The hierarchical structure for Levels "5" to "6" is "complete", but not composed entirely of functional attributes. The Level "5" **attributes** are functional in nature, i.e."functional". However, Level "6" is not functional in nature. In fact it is not composed of **attributes** at all. Level "6" is composed of the **physical options / alternatives** to be evaluated by the AHP. The "bottom" level is the only AHP hierarchy level that need not be functional in nature.

The third step is to construct the pair-wise relative preference ratio matrices necessary to analytically calculate: (1) the relative importance (weights) of **attributes** at a given level with respect to a given **attribute** at the next higher level, and (2) the relative capability (weights) of **alternatives** at the lowest level with respect to a given **attribute** at the next higher level, i.e. at the next to the lowest level of the hierarchy.

Level "0" is the top level and requires the construction of no pair-wise relative preference ratio matrices since the importance of its single **attribute**, Mission Effectiveness, is trivially one (1.0).

Level "1" requires one 2x2 matrix construction, involving the relative importance (weight) of Regional War and Global War capabilities with respect to overall Mission Effectiveness.

Level "2" requires two 3x3 matrix constructions. The two 3x3 pair-wise relative preference ratio matrices constructions required are: (1) a pair-wise relative preference ratio matrix for the three level "2" **attributes**, Sea Control, Power Projection; Sealift/SLOC Protection with respect to their relative importance (weight) in a Regional War, and (2) a separate 3x3 pair-wise relative preference ratio matrix for Sea Control, Power Projection; Sealift/SLOC Protection with respect to their relative importance (weight) in a Global War.

The number of pair-wise relative preference ratio matrices required for any given hierarchical level is the number of hierarchical **attributes** mapped onto in the next higher hierarchical level. The dimensions of a pair-wise relative preference ratio matrix is the number of **attributes** (**alternatives** at the "bottom" level) mapped at the given hierarchical level. Thus:

(1) Level "3" requires three 8x8 matrix constructions,

(2) Level "4" requires eight 14x14 matrix constructions,

(3) Level "5" requires fourteen 8x8 matrix constructions;

(4) Level "6" requires one-hundred twelve NxN matrix constructions, where N is the number of alternatives being considered.

Note: Eight Warfare Task specific fundamental attributes times fourteen Warfare Tasks is one-hundred twelve.

In all a total of 140 separate pair-wise relative preference ratio matrices constructions are required for the proposed AHP hierarchy. The construction of 140 matrices is not a simple task. However, given the complexity of a Naval Task Force, 140 is a modest number.

The Level "5" matrix constructions would have involved fourteen 112x112 matrix constructions if the hierarchy had been structured to be complete. Significant savings in both personnel resources and computer capability, not to mention time, are achieved by the incomplete hierarchical structure suggested. The selection of a reasonably small number of **alternatives**, N, in Phase-2 of the overall Naval Task Force assessment process can produce substantial efficiencies as well. Values of N greater than four or five may be impractical. Values of N above nine are not recommended. Other efficiencies may be gained by clustering some of the fourteen Warfare Tasks of Level "4" into "clustered" Warfare Tasks. If reasonable, such a clustering resulting in nine or less Level "4" **attributes** might be considered. This would provide additional efficiencies in the AHP.

An individual pair-wise relative preference ratio matrix , R, must be generated for the hierarchical **attributes** of a given level with respect to a criterion set by a related hierarchical **attribute** of the next higher hierarchical level. In a given pair-wise relative preference ratio matrix, R, an attributes ratio , r_{ij} , is by convention a measure of the dominance of the i th hierarchical **attribute** of a given level over the j th hierarchical **attribute** of that level with respect to the criterion set by a given hierarchical **attribute** of the next higher hierarchical level. Similarly, an individual pair-wise relative preference ratio matrix , R, must be generated for the hierarchical **alternatives** of the "bottom" level with respect to a criterion set by a related hierarchical **attribute** of the next to the "bottom" hierarchical level. As noted above, the object of the construction of a pair-wise relative preference ratio matrix is to be able to find the relative importance (weight) of each of the appropriate hierarchical **attributes** of a given level (**alternatives** at the "bottom" level) with respect to a related hierarchical **attribute** at the next higher level.

Procedures for generating a relative preference ratio matrix, and finding consistent estimates of the required associated **attribute** preference weights are presented in Appendix A. The Saaty pair-wise relative preference ratio scale, and the Eigenvector Method for analytically finding weights from a pair-wise relative preference ratio matrix found in Appendix A are the analytical foundations of Saaty's AHP version of the Hierarchical Additive Weights (HAW) process. The independence or interdependence of attributes at a given level is also a real concern in the development of a hierarchy and the related preference ratio matrices. For a discussion of how the AHP addresses interdependencies among attributes see Saaty [3].

Step four involves the development of numerical estimates of the pair-wise preference ratios for the relative preference ratio matrices developed in step three.

Step four is the most important and labor intensive step in AHP. It must be carefully planned, and executed. The numerical estimates must reflect the considered judgments of decision makers at the appropriate military and political level. The decision makers from the various levels must be willing and able to make an appropriate effort to develop consistent numerical estimates.

Multiple judgements of the numerical estimates for a given matrix by an appropriate group of decision makers (expert panel) is highly desirable. A single set of numerical judgements for a given matrix can be obtained by group consensus, e.g. use of a Delphi procedure [5] . Multiple judgements can also be synthesized by calculating the geometric mean as suggested by Saaty [3]. The use of both, where the geometric mean is used following each iteration of a Delphi procedure is suggested to facilitate convergence to a consistent group consensus.

Separate groups of decision makers (expert panels) are suggested for the development of the numerical estimates of matrices required for the various levels of the AHP hierarchy. For example, some Level "0" through Level "2" related matrices might require a group of decision makers from DOD, the CINCs; and CNO. Some Level "2" through Level "4" related matrices might require a group of decision makers from the CINCs, OPNAV, and the SYSCOMs. The Level "4" through Level "6" related matrices might require several groups, each composed of decision makers who are experts in a given Warfare Task from the CINCs, OPNAV; and the SYSCOMs. This is not to suggest 140 different groups. However, some hierarchical formulation of groups based on the military and political scope and/or AHP hierarchical level associated with the matrix being addressed is highly recommended.

Step five can begin once a group has come to an initial consensus on the numerical estimates of an assigned matrix. In fact step five can and should begin well before all the groups have come to an initial consensus for all the matrices required.

As agreed, consensus matrices become available from a group, the AHP analysts can begin calculating estimates of the attribute priorities (weights) for a given agreed matrix and test the consistency of the pair-wise preference ratio estimates of the agreed matrix. The appropriate AHP mathematical procedures are found in Appendix A. In general, the procedures could be performed in a few minutes on a personal computer , e.g. using standard AHP software, or general mathematical software such as MathCAD. In fact, with sufficient computer resources and software, the required procedures could be performed as an integral part of the group's activities. This would most certainly facilitate, in near "real time" , the convergence of a group to a set of consistent agreed matrices and associated attribute weights.

Step six is the consolidation of the final results of steps three, four, and five.

Step seven is performed by the AHP analysts. It involves using the AHP related Hierarchical Additive Weights procedures discussed in Appendix A to calculate an 1xN Mission Effectiveness priority vector for the N considered Task Force Architectural **alternatives**.

Step eight is the evaluation of the consistency of the entire hierarchy. This is done by first multiplying each ratio matrix's consistency index, CI, calculated in step five by the priority (weight) of the corresponding criterion, i.e. the associated next higher level alternative established criterion, and adding the products to find the overall hierarchy consistency index. Next repeat the above calculation using corresponding random ratio matrix consistency Index values from Appendix A in place of the ratio matrix consistency indices used above to find the overall random consistency index. The consistency ratio for the entire hierarchy is the consistency index for the overall hierarchy divided by the overall random consistency index [3]. If the overall consistency ratio is greater than 0.1 (10%), then the overall quality of the ratio matrix numerical estimates should be improved, and/or the hierarchical structure is flawed. If this is the case, an iteration of the AHP beginning again with step two is indicated. Otherwise, an initial analysis process has been completed.

COMMENTS AND RECOMMENDATIONS

The specific Task Force performance analysis plan outlined above is provided as a demonstration of the utility of the AHP methodology. It is a preliminary first cut . It can serve as a starting point for the formal development of a decision maker guided, AHP analyst planned, Naval Task Force performance analysis process based on the AHP Methodology.

The design and implementation of an AHP is not a step by step rote process. It is an art! When and if the AHP is selected for use as a Task Force performance analysis process, the appropriate decision makers, and analysts skilled in the AHP art should sit down together and develop an explicit analysis plan that follows the AHP steps as outlined by Saaty.

The proposed Task Force performance analysis methodology is viewed as:

(1) Effective in that it is addresses the central problem and provides for a solution methodology that involves the key decision makers in its design and implementation. The AHP also builds consensus in a straight forward way.

(2) Timely in that the initial design and implementation phase should take less than a year. Follow on iterative use of the design would only require assessments of the ratio matrices, and calculation of weights for the new alternatives of Level "6" considered in a follow on POM cycle assessment. Unless there are significant changes in the national interests, and associated policy and grand strategy changes, the level "5" and above attribute weights need not be recalculated. Thus, iteration of the proposed process should be executable in less than six months.

(3) Traceable and repeatable due to the inherent in the formal analytical nature of the AHP methodology.

(4) Understandable in that the AHP methodology combines two fundamental and intuitively appealing approaches to problem solving: (1) the systems approach with its focus on a system as a whole, and (2) the deductive reasoning approach of applied science with its focus on the component parts of a system.

The demonstrated utility provided above, and the practical nature of the AHP methodology, recommend its adoption for Task Force performance analysis.

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APPENDIX A

MULTIPLE ATTRIBUTE DECISION MAKING FORMULATIONS

MULTIPLE ATTRIBUTE DECISION MAKING FORMULATIONS

GENERAL FORMULATION

A general, generic, matrix algebra formulation of Multiple Attribute Decision Making (MADM) is presented.

Let $D = [\, d_{ij} \,]$ be an $m \times n$ decision matrix where m is the number of decision making **alternatives (rows)**, and n is the number of **attributes (columns)** ascribed to an alternative. Let the row vector

$$d_{i.} = [\, d_{i1}, \ldots, d_{in} \,]$$

be the n attribute (column) values for alternative i. Let column vector

$$d_{.j}^{T} = [d_{1j}, \ldots, d_{mj}]^{T}$$

be the m alternative (row) values for attribute j.

Let f_k be the k^{th} objective function of a set of p decision objectives. For the i^{th} alternative of a set of m alternatives, let

$$f_k^i = F(d_{i1}, \ldots, d_{in} \mid \text{given an alternative } i\,) .$$

The alternative, i'_k that gives

$$i'_k = \max_i \; (\, f_k^i \,)$$

is the alternative that is an "optimal" decision with respect to objective k. If i'_k is the same alternative, i*, for all objectives, k=1, 2,..., p, then alternative i* is the "optimal" decision of a MADM process. Note, i* is "optimal" only with respect to the set of objectives defined by the set of objective functions $\{f_1, \ldots, f_p\}$. Such a unique alternative as i* generally does not exist in practice. If it did, there would be no conflict among the alternatives, and the MADM process would be straight forward and simple.

MADM WITH "NON-OPTIMAL" ALTERNATIVES

The array of methods for MADM is extensive. Preferred methods depend on the type of information available to the decision maker and the salient features and nature of the information [1]. If attribute preference information is known or estimatable with respect to a cardinal scale, several methods are potentially useful. The methods discussed are the Simple Additive Weighting (SAW) method, and the Hierarchical Additive Weighting (HAW) method. A discussion of the Linear Assignment , Elimination et Choice Translating Reality (ELECTRE), and Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS) methods can be found in Hwang and Toon [1].

The Weighted Least Square and Eigenvector methods for estimating attribute preference information, i.e. normalized weights, from an attribute pair-wise preference matrix, and observed attribute values transformation and normalization procedures are also presented.

ATTRIBUTE PREFERENCE ESTIMATION METHODS

The considered MADM methods all require attribute preference information. This information is assumed to be available as cardinal scale data. Preference data is usually expressed by a set of attribute preference weights which are greater than zero and normalized so that their sum over all attributes is one. Thus, for or n attributes, let the set of weights, $w_i > 0$, form a $1 \times n$ matrix

$$W = [w_1, w_2, \dots, w_j, \dots, w_n],$$

where

$$\sum_{i=1}^{n} w_i = 1.$$

The "true" weights are usually not known explicitly, and thus must be estimated. If, however, the "true" weights were known, then a pair-wise, relative preference ratio, matrix, R, could be written as an $n \times n$ matrix

$$R = \left(r_{ij} = \frac{W_i}{W_j}\right).$$

Thus, an estimate of the ratio matrix, R, can be expressed as $\hat{R} = [\hat{r}_{ij}]$, where $\hat{r}_{ij}$ is an estimate of the pair-wise ratio $[W_i / W_j]$.

A recommended pair-wise, relative preference, ratio scale is the Saaty scale [1, 2] presented below:

Where the **row i attribute dominates a column j attribute** with respect to a given criteria, for a given attribute pair and objective function, $\hat{r}_{ij}$ is set to the following values:

$\hat{r}_{ij} = 1$ for equal importance of attributes for the given objective function,
$\hat{r}_{ij} = 3$ for weak importance of attribute i over attribute j,
$\hat{r}_{ij} = 5$ for adjudged strong importance of attribute i over attribute j,
$\hat{r}_{ij} = 7$ for demonstrated strong importance of attribute i over attribute j;
$\hat{r}_{ij} = 9$ for absolute importance of attribute i over attribute j.

The values $\hat{r}_{ij} = 2, 4, 6$, or 8 are assigned when intermediate, compromise values, for the importance of attribute i over attribute j are needed.

Where the **row i attribute is dominated by a column j attribute** with respect to a given criteria, for a given attribute pair and objective function, $\hat{r}_{ij}$ is set to the following values:

$\hat{r}_{ij} = 1$ for equal importance of attributes for the given objective function,
$\hat{r}_{ij} = 1/3$ for weak importance of attribute j over attribute i,

$\hat{r}_{ij}$ = 1/5 for adjudged strong importance of attribute j over attribute i ,
$\hat{r}_{ij}$ = 1/7 for demonstrated strong importance of attribute j over attribute i ;
$\hat{r}_{ij}$ = 1/9 for absolute importance of attribute j over attribute i .

The values $\hat{r}_{ij}$ = 1/2, 1/4, 1/6, or 1/8 are assigned when intermediate, compromise values, for the importance of attribute j over attribute i are needed.

Note that the above scale maintains the reciprocal property $\hat{r}_{ij} = [1 / \hat{r}_{ji}]$ of the ratio matrix, R, in its estimate $\hat{R}$. Thus only the upper diagonal of $\hat{R}$ needs to be estimated, since the diagonal values of $\hat{R}$ are trivially one.

To find a Weighted Least Square method estimate $\hat{W}$ of W, for a given $\hat{R}$, let an error of the estimate term be

$$\varepsilon^*_{ij} = (\hat{r}_{ij} - r_{ij}),$$

or equivalently, since $0 < w_j \leq 1$,

$$\varepsilon_{ij} = \varepsilon^*_{ij} \; w_j = (\hat{r}_{ij} w_j - w_i).$$

Using ε_{ij} as an error of the estimate term, let

$$\hat{W} = \min_{\{W\}} \sum_{i=}^{n} \sum_{j=1}^{n} (\varepsilon_{ij})^2 = \min_{\{W\}} \sum_{i=}^{n} \sum_{j=1}^{n} (\hat{r}_{ij} w_j - w_i)^2 ,$$

with the constraint

$$\sum_{i=1}^{n} w_i = 1$$

A solution, $\hat{W}$, to the above minimum least squares equation with its constraint can be found by solving for the extreme (minimum) of the associated Lagrangian function

$$L(w_1, \dots , w_n, \lambda) = \sum_{i=}^{n} \sum_{j=1}^{n} (\hat{r}_{ij} w_j - w_i)^2 + 2 \lambda ((\sum_{i=1}^{n} w_i) - 1),$$

where λ is a Lagrangian multiplier. As a result, $\hat{W}$, is obtained by solving the matrix equation [1].

$$[\hat{w}_1 , \dots , \hat{w}_n , \lambda]^T = [b_{ij}]^{-1} [0, \dots ,0, 1]^T,$$

where $B = [b_{ij}]$ is an $(n+1) \times (n+1)$ symmetric matrix defined by

$b_{ij} = -(\hat{r}_{ij} + \hat{r}_{ji})$ for $i = 1, \ldots, n$, $j = 1, \ldots, n$, and $i \neq j$,

(i.e, for a given fixed i and $j \neq i$, let $j = 1, \ldots, n$ to generate the off diagonal elements for both i and j less than or equal to n),

$b_{k,(n+1)} = b_{(n+1),k} = 1$ for $k = 1, \ldots, n$,

$$b_{ii} = (n-1) + \sum_{k=1;k\neq i}^{n} (\hat{r}_{ki})^2 \quad \text{for } i = j;\ i = 1, \ldots, n,$$

(i.e., for a given fixed i, let $k = 1, \ldots, i-1, i+1, \ldots, n$ to generate the diagonal elements for $i = 1, \ldots, n$),

and

$b_{(n+1),(n+1)} = 0.$

From the above, the matrix equation, B, for $n = 3$ is

$$\begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} \\ b_{21} & b_{22} & b_{23} & b_{24} \\ b_{31} & b_{32} & b_{33} & b_{34} \\ b_{41} & b_{42} & b_{43} & b_{44} \end{bmatrix}$$

where

$$\begin{aligned}
b_{11} &= 2 + (\hat{r}_{21})^2 + (\hat{r}_{31})^2, \\
b_{22} &= 2 + (\hat{r}_{12})^2 + (\hat{r}_{32})^2, \\
b_{33} &= 2 + (\hat{r}_{13})^2 + (\hat{r}_{23})^2, \\
b_{21} &= b_{12} = -(\hat{r}_{21} + \hat{r}_{12}), \\
b_{31} &= b_{13} = -(\hat{r}_{31} + \hat{r}_{13}), \\
b_{32} &= b_{23} = -(\hat{r}_{32} + \hat{r}_{23}), \\
b_{41} &= b_{42} = b_{43} = b_{14} = b_{24} = b_{34} = 1; \\
b_{44} &= 0.
\end{aligned}$$

Thus,

$$[\hat{w}_1, \hat{w}_2, \hat{w}_3, \lambda]^T = [b_{ij}]^{-1} [0, 0, 0, 1]^T.$$

To find an Eigenvector method estimate $\hat{W}$ of W, for a given $\hat{R}$, note that

$$R = \left(r_{ij} = \frac{W_i}{W_j}\right)$$

is a "reciprocal matrix" with all positive elements. Note also that R is consistent in that

$$(r_{ik})(r_{kj}) = \left(\frac{W_i}{W_k}\right)\left(\frac{W_k}{W_j}\right) = \left(\frac{W_i}{W_j}\right) = r_{ij} .$$

Forming the matrix equation below yields the interesting result

$$R \times W^T = \left(r_{ij} = \frac{W_i}{W_j}\right)([w_1, w_2, \dots, w_j, \dots, w_n])^T = n\, W^T,$$

or

$$(R - n\,I)W^T = 0,$$

where I is the nxn identity matrix.

The eigenvalue, eigenvector pairs of R are solutions to the matrix equation

$$(R - \lambda I)\xi^T = 0,$$

thus $\{n, W\}$ is an eigenvalue, eigenvector pair of R. In fact it is the only and trivial solution due to the consistency property of R.

In general $\hat{R}$ is not perfectly consistent. However, the reciprocal property of $\hat{R}$, and a careful estimation of its elements by experts should make the estimated pair-wise ratio elements closer to consistent than to being random numbers. Thus if we solve

$$(\hat{R} - \lambda I)\xi^T = 0,$$

for λ_{max} and its associated eigenvector ξ then for a reasonably consistent $\hat{R}$ an estimate of W is given by

$$\hat{W} = \xi \cdot$$

Saaty [2] suggests that an index of the consistency of $\hat{R}$ is given by

$$CI = |(\lambda_{max} - n)| / 2 .$$

Saaty has calculated expected CI values for random reciprocal matrices of size n. Saaty's CI values for random consistency give:

matrix size n	1	2	3	4	5	6	7	8	9	10
CI_{random}	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Saaty defines a consistency ratio, CR as

$$CR = CI(\lambda_{max}, n) / CI_{random}(n).$$

CR values of 10% (0.1) or less are desirable for $n \geq 3$. If this is not the case the quality of the associated $\hat{R}$ matrix is suspect and $\hat{R}$ should be re-estimated [2].

An estimation of the weights, W, by the prudent selection of an attribute weights estimation method is critical to creditable MADM results. A poor or biased procedure can and will adversely effect MADM outcomes. The use of one or both of the above analytic methods (vice an ad-hoc or "group grope" procedure) is recommended.

DECISION MATRIX TRANSFORMATION AND NORMALIZATION

The considered methods all utilized a "best" alternative selection method based on an evaluation of objective functions. The objective function calculations all utilize quantitative attribute weights information, and comparable, e.g. linear, monotonic, normalized, quantified attribute values.

For n attributes and m alternatives let D^o be an $m \times n$ decision matrix of observed attribute values over all alternatives. A transformation procedure converts the observed (quantitative or qualitative / fuzzy) attribute values, d^o_{ij}, into quantified measurement scale values, x_{ij}.

For linear, monotonic, quantitative observed attribute values, transformation is trivial. In general, values are usually directly observed as quantitative scale values. Examples are:

(1) Ordinal scale, rank order value of an attribute vis-a-vis an alternative with respect to the other alternatives.

(2) Relative numerical scale value of the distance with respect to some arbitrary origin for an attribute vis-a-vis an alternative.

(3) Absolute numerical scale value of the distance with respect to a non-arbitrary origin for an attribute vis-a-vis an alternative.

A numerical scale value may be either the total distance from the origin for a given attribute vis-a-vis an alternative, or the relative distance (difference) along the scale for a given attribute vis-a-vis an alternative relative to the other alternatives.

If the d^o_{ij} values for a given attribute j are not monotonic, but are monotonic, or better yet linear monotonic, in a function $F^j(d^o_{ij})$, then it is desirable to let $x_{ij} = F^j(d^o_{ij})$ be a transformation process for attribute j. Examples are:

(1) Monotonic or linear in the Log, where

$$x_{ij} = \mathrm{Log}\,(d^o_{ij} \mid \text{fixed } j),$$

(2) Monotonic or linear in the q^{th} root, where

$$x_{ij} = (d^o_{ij} \mid \text{fixed } j)^{1/q},$$

(3) Monotonic or linear in the exponential of e where

$$x_{ij} = \exp (d^o_{ij} \mid \text{fixed } j) ;$$

(4) Monotonic or linear in the quadratic, where

$$x_{ij}=a_0 + a_1(d^o_{ij} \mid \text{fixed } j) +a_2(d^o_{ij} \mid \text{fixed } j)^2.$$

Such transformations assure that transformed attribute values are monotonic, i.e. "more is better" or "more is not better."

Qualitative / fuzzy observed attributes must be quantified. The simplest monotonic quantification scheme is to use an ordinal scale, e.g. rank order of an attribute over the alternatives. A useful x_{ij} monotonic relative numerical scale for a given attribute j is:

$$\boxed{\boxed{1\text{-}2\text{-}3}\boxed{4\text{-}5\text{-}6}\boxed{7\text{-}8\text{-}9}},$$

where for "more is better" attributes $\boxed{1\text{-}2\text{-}3}$ is the low range, $\boxed{4\text{-}5\text{-}6}$ is the mid range, and $\boxed{7\text{-}8\text{-}9}$ is the high range. For "more is not better" attributes, such as cost, $\boxed{1\text{-}2\text{-}3}$ is the high range, and $\boxed{7\text{-}8\text{-}9}$ is the low range. If necessary, the values 0 and 10 can be used for extreme values, e.g. the minimum and maximum realizable values. Quantification by an absolute numerical scale is not generally practical due to the fuzzy nature of a qualitative attribute.

Normalization is used to convert the various attribute scales into comparable, e.g. normalized / "unit-less" , scales of similar length. This facilitates objective function computations, since objective function calculations all utilize quantitative attribute weights information, and comparable, e.g. linear, monotonic, normalized, quantified attribute values.

Potential normalizations procedures, for fixed attribute j , where d_{ij} are comparable unit-less attribute values, and x_{ij} are transformed quantified observed attribute values, are:

(1) Vector Normalization where

$$d_{ij} = \frac{x_{ij}}{\sqrt[2]{\sum_{i=1}^{m}(x_{ij})^2}} ,$$

(i.e. $d_{ij} = 1$ for the norm of $(x_{ij} \mid j)$).

(2) Maximum Value Normalization where
for all attributes "more is better" case

$$d_{ij} = \frac{x_{ij}}{\max\limits_{i} x_{ij}} \; ; \; d_{ij} \le 1,$$

for all attributes "more is not better" case

$$d_{ij} = 1 - \frac{x_{ij}}{\max\limits_{i} x_{ij}} \; ; \; 0 \le d_{ij} \, ,$$

and for a mix of cases among attributes, for "more is better" case

$$d_{ij} = \frac{x_{ij}}{\max\limits_{i} x_{ij}} \; ; \; d_{ij} \le 1,$$

and for "more is not better" case

$$d_{ij} = \frac{\frac{1}{x_{ij}}}{\max\limits_{i}\left(\frac{1}{x_{ij}}\right)} = \frac{\min\limits_{i} x_{ij}}{x_{ij}} \; ; \; d_{ij} \le 1 \, .$$

(3) Range Normalization of attributes where
for "more is better" case

$$d_{ij} = \frac{x_{ij} - \left(\min\limits_{i} x_{ij}\right)}{\left(\max\limits_{i} x_{ij}\right) - \left(\min\limits_{i} x_{ij}\right)} \; ; \; 0 \le d_{ij} \le 1,$$

and for "more is not better" case

$$d_{ij} = \frac{\left(\max\limits_{i} x_{ij}\right) - x_{ij}}{\left(\max\limits_{i} x_{ij}\right) - \left(\min\limits_{i} x_{ij}\right)} \; ; \; 0 \le d_{ij} \le 1 \, ;$$

(4) Sum Value Normalization of attributes where for "more is better" case

$$d_{ij} = \frac{x_{ij}}{\sum\limits_{i=1}^{m} x_{ij}} \; ; \; \sum_{i=1}^{m} d_{ij} = 1,$$

and for "more is not better" case

$$d_{ij} = \frac{\frac{1}{x_{ij}}}{\sum_{i=1}^{m} \frac{1}{x_{ij}}} ; \quad \sum_{i=1}^{m} d_{ij} = 1 .$$

All of the above procedures have advantages and disadvantages [2]. As with attribute weights estimation, a prudent selection of attribute transform and normalization procedures is critical to creditable MADM results. For example transforming observations to all positive, linear monotonic, "more is better" values simplifies the procedure. Poor or biased selections can and will adversely affect MADM outcomes.

SIMPLE ADDITIVE WEIGHTING METHOD

The Simple Additive Weighting Method (SAW) uses a single objective function for the selection of the best alternative. The MADM formulation is straight forward, given a prudent estimation of attribute weights, and a carefully transformed, normalized decision matrix of comparable, quantified attribute values.

Mathematically SAW calculates the objective function for a given alternative i, as the weighted sum of the attribute values [$d_{i.}$] . Thus

$$f_1^i = \mathcal{f} (d_{ij} \mid \text{given an alternative } i) = d_{i.} \hat{W}^T = [d_{i1}, \dots , d_{in}] [\hat{w}_1 , \dots , \hat{w}_n]^T.$$

For all alternatives the calculation is

$$F_1^T = [f_1^1 , \dots , f_1^i , \dots , f_1^m]^T = D \hat{W}^T = [d_{ij}] [\hat{w}_1 , \dots , \hat{w}_n]^T.$$

The alternative i'_1 that gives

$$i'_1 = \max_{i=1\text{-to-}m} (f_1^i)$$

is the alternative that is an "optimal" decision with respect to objective 1. Since i'_1 is the "optimal" overall alternative, i^*, for a singular objective set, where $p = 1$, then $i^* = i'_1$ is the "optimal" decision alternative for the SAW MADM process.

The SAW method can be extended to a complex additive method where several objective functions, each with its own separate weights, are used. If the SAW method is applied to the resulting objective function set results as if they were the elements of a second decision matrix, with its own separate weights, the SAW results are the weighted sums of the objective function values of the complex additive method. An extension of this notion leads to the Hierarchical Additive Weighting Method.

HIERARCHICAL ADDITIVE WEIGHTING METHOD

The Hierarchical Additive Weighting Method (HAW) uses a hierarchical "best" alternative selection method based on evaluations of a series of hierarchical "nested" objective functions. The objective function calculations all utilize quantitative attribute weights information.

For the observed comparable values case with m alternatives (hierarchical elements at the lowest level) and n attributes (hierarchical elements at next to the lowest level), let D^o be an $m \times n$ decision matrix of observed attribute values over all alternatives. Assume a transformation procedure has converted the observed (quantitative or qualitative / fuzzy) attribute values, d^o_{ij}, into comparable, linear monotonic, quantified measurement scale values, x_{ij}, where $0 \leq x_{ij}$. Further assume that the x_{ij} values have been Sum Value normalized with respect to each attribute $j = 1, \ldots, n$, such that, for the "more is better" attributes in the set,

$$d_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad ; \quad \sum_{i=1}^{m} d_{ij} = 1,$$

and for the "more is not better" attributes in the set,

$$d_{ij} = \frac{\frac{1}{x_{ij}}}{\sum_{i=1}^{m} \frac{1}{x_{ij}}} ; \quad \sum_{i=1}^{m} d_{ij} = 1 .$$

The resulting transformed and normalized decision matrix $D = [\, d_{ij} \,]$ has the character of a lowest level weighting matrix, W_h, where h is the number of hierarchical levels. Each set of d_{ij} values for fixed j forms a column vector of D that is an estimate of the relative importance (weighting) of the lowest hierarchical level elements (alternatives) with respect to the next to the lowest level hierarchical elements (basic attributes).

At this point we have what is similar to a first step in a SAW procedure where Sum Value normalization is used. If we let the normalized $m \times n$ decision matrix $D=W_3$ in a three level hierarchy, $h=3$, and estimate the importance (e.g. using the ratio matrix method) of each basic attribute with respect to the single top level of the hierarchy element, e.g. figure of merit (FOM), we can obtain an $n \times 1$ weighting column vector matrix W_2, for the basic attributes with respect to a single top level element, FOM. Since the FOM is a single value, $W_1 = [\, 1 \,]$ is a 1×1 matrix, i.e. the trivial weighing at the top of the hierarchy. This three level HAW procedure is the same as the SAW procedure where Sum Value normalization is used, i.e. where, the $m \times 1$ matrix of alternative rankings is given by

$$FOM = W_3 \; W_2 \; W_1 .$$

Thus the SAW procedure can be structured as a special case of the HAW procedure.

The HAW method thus has its advantage over the SAW method when the number of hierarchical levels is greater than three.

THE ANALYTIC HIERARCHY PROCESS

The Analytical Hierarchy Process (AHP) developed by Thomas L. Saaty is a special case of the Hierarchical Additive Weighting Method (HAW) [1]. Saaty's recent 1990 text [2] addresses the issues of how to use the AHP in decision making. The text's focus is on simple examples, how to structure a problem hierarchy, and how to use the AHP method to assess priorities among decision alternatives. The text makes little or no mathematical demands.

The AHP form of the HAW method has been selected as the Naval Task Force performance assessment methodology of choice. The specifics of the proposed AHP structure are provided in the body of the text.

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1. Ching-Lai Hwang and Kwangsun Toon, *Multiple Attribute Decision Making Methods and Applications: A State—of-the-Art Survey* (Springer-Verlag, New York, NY, 1981).

2. T. L. Saaty, *Decision Making for Leaders: The Analytic Hierarchy Process for Decisions in a Complex World* (RWS Publications, Pittsburgh, PA, 1990).

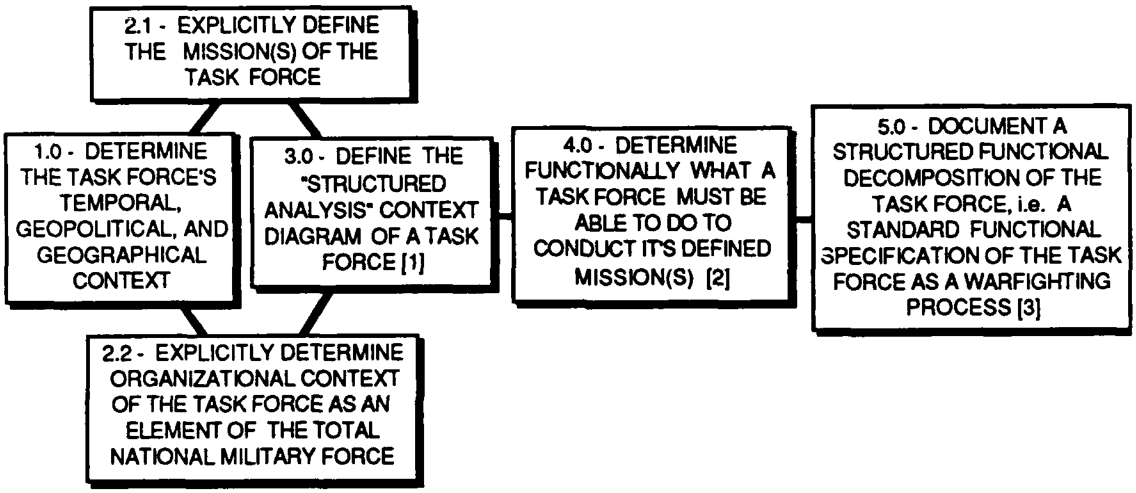
APPENDIX B

ASSESSMENT PROCESS DETAILS

ASSESSMENT PROCESS DETAILS

PROCESS PHASES

Details of the four phases of the Task Force assessment process shown in Figure 1 of the main text are shown in Figures B1 through B4 below.

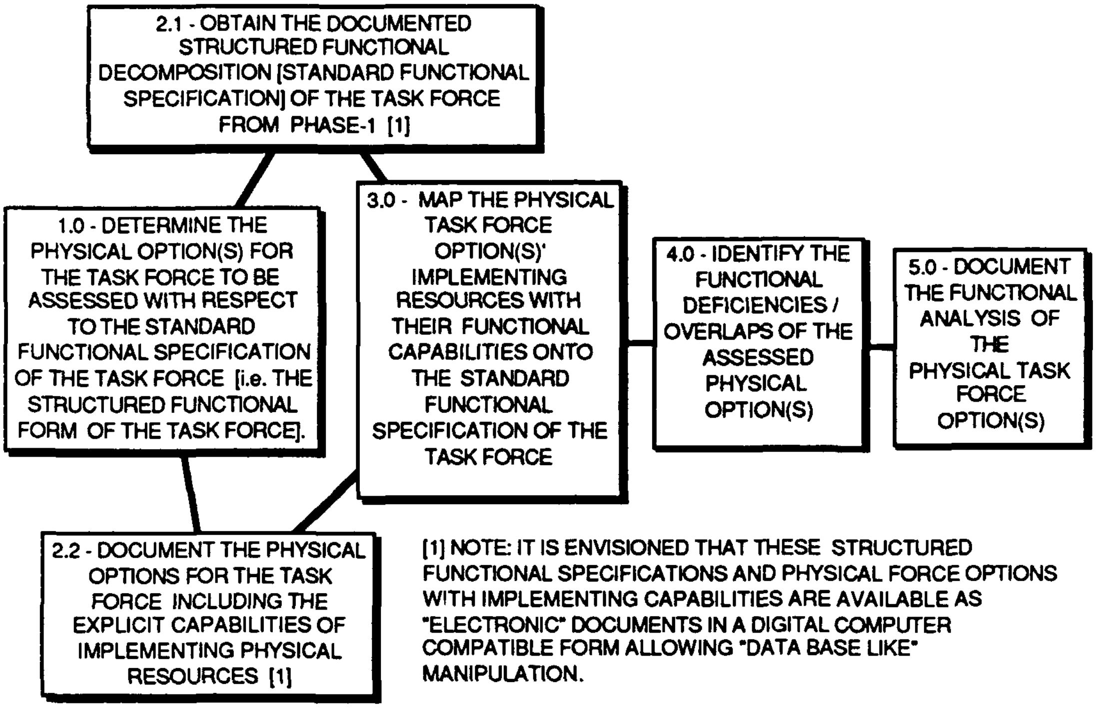


[1] NOTE: EXPLICITLY DETERMINE AND DEFINE ALL OF THE INTERFACES OF THE TASK FORCE AS A "SUB PROCESS" OF THE NATIONAL MILITARY FORCE PROCESS.

[2] NOTE: AT THIS POINT IN THE PROCESS, THE FOCUS IS ON WHAT THE FORCE MUST BE ABLE TO DO, NOT ON HOW IT IMPLEMENTS A FUNCTION AS A PHYSICAL SYSTEM.

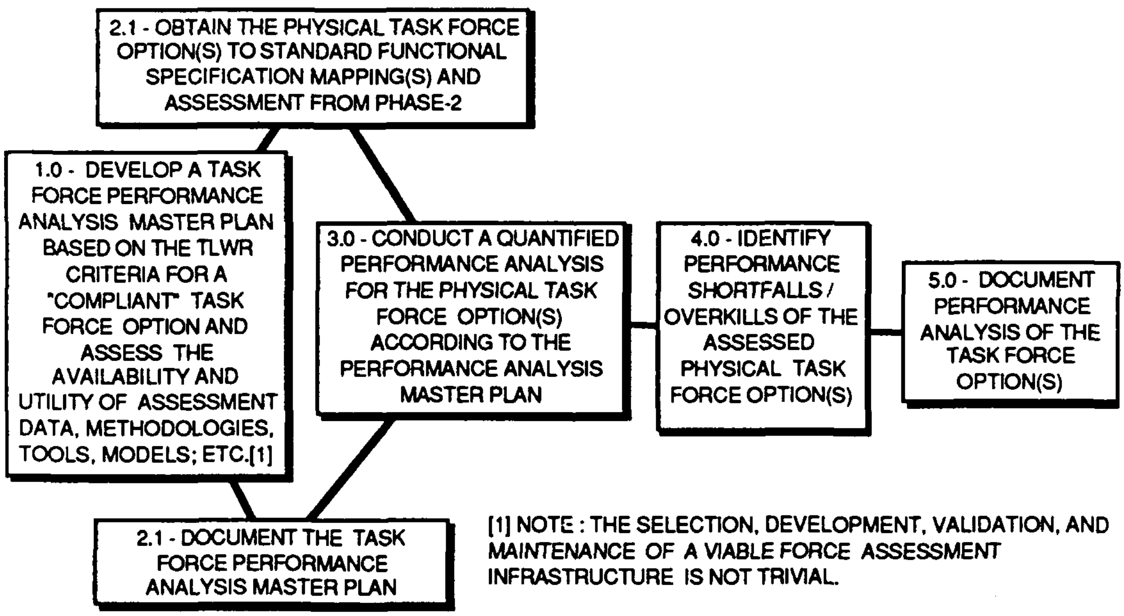
[3] NOTE: FUNCTIONAL DECOMPOSITION SHOULD INCLUDE NOT ONLY DEFINITIONS OF "WHAT IT MUST DO" FUNCTIONS BUT ALSO THE STRUCTURAL INTERFACES BETWEEN THE RELATED FUNCTIONS. THIS MIGHT ALSO INCLUDE A DESCRIPTION OF ALL REQUIRED "FUNCTIONAL / NOTIONAL STORES", e.g. OF INFORMATION, MISSILES, BOMBS, DATA, FUEL, DOCTRINE MANUALS, etc., AND THEIR INTERRELATIONSHIPS. IF THE ASSIGNED MISSION(S) DICTATE, THE ABOVE MUST BE DONE EXPLICITLY FOR ALL UNIQUE OPERATIONAL STATES OF THE TASK FORCE.

FIGURE B1. PHASE-1: FUNCTIONALLY DECOMPOSE A TASK FORCE



[1] NOTE: IT IS ENVISIONED THAT THESE STRUCTURED FUNCTIONAL SPECIFICATIONS AND PHYSICAL FORCE OPTIONS WITH IMPLEMENTING CAPABILITIES ARE AVAILABLE AS "ELECTRONIC" DOCUMENTS IN A DIGITAL COMPUTER COMPATIBLE FORM ALLOWING "DATA BASE LIKE" MANIPULATION.

FIGURE B2. PHASE-2: FUNCTIONALLY ANALYZE PHYSICAL OPTION(S)



[1] NOTE : THE SELECTION, DEVELOPMENT, VALIDATION, AND MAINTENANCE OF A VIABLE FORCE ASSESSMENT INFRASTRUCTURE IS NOT TRIVIAL.

FIGURE B3. PHASE-3: CONDUCT PERFORMANCE ANALYSIS

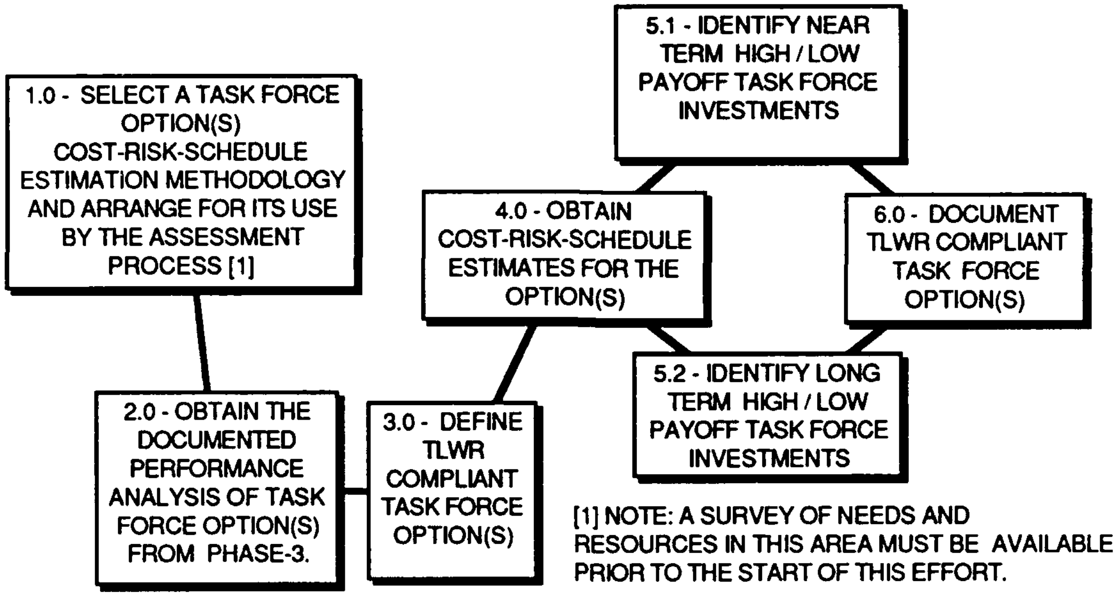


FIGURE B4. PHASE-4: DEVELOP TLWR COMPLIANT OPTIONS

APPENDIX C

GENERIC FUNDAMENTAL PRIMITIVE FUNCTIONS

GENERIC FUNDAMENTAL PRIMITIVE FUNCTIONS

FUNDAMENTAL DEFINITIONS

Level "5" of the proposed AHP hierarchy is derived from observing the utility of a generic set of "lower" level functional decomposition attributes in previous Warfare Task functional decompositions [1], i.e. Receive, Sense, Plan, Observe, Assess, Execute, Issue, and Act. The development and use of these generic fundamental or primitive functions (attributes) were inspired by the work of Paul Girard [2].

Plan, Observe, Assess, and Execute are the generic fundamental functions of command. They generically cover the necessary command functions of the lowest level to the highest level of command. They can be described as follows:

Observe is the function of assembling information and recognizing its form in the context of a situation and its environment.

Assess is the function of evaluating the relevance of an observed situation in the context of mission objectives and the environment.

Plan is the function of generating and selecting a course of action.

Execute is the function of formulating the selected course of action into action directives and the enforcement of the directives.

Sense and Act are the generic fundamental functions of physically interacting or coupling with the physical world and its environment. They generically cover the functions necessary to interact with or make an impact on the real world. In general they are the carrying out of action directives or standing orders of command. They can be described as follows:

Sense is the function of probing the real physical world for information about physical things in the environment or conditions of the environment.

Act is the function of producing an effect on a physical object in the real world or the physical environment.

Receive and issue are the generic fundamental functions of communicating. They are the generic functions necessary to transfer information from one of the other functions to another. They can be described as follows:

Receive is the function of accepting or taking in information.

Issue is the function of sending or giving out information.

When the above functions are applied to a specific Naval Warfare Task such as AAW, the set of eight functions becomes AAW Receive, AAW Sense, AAW Plan, AAW Observe, AAW Assess, AAW Execute, AAW Issue, and AAW Act, a set of eight fundamental or primitive functions necessary to conduct AAW.

Similarly, when the above functions are applied in turn to each of the Naval Warfare Tasks necessary to conduct Naval Warfare, the result is a complete set of fundamental or primitive functions necessary to the conduct of Naval Warfare, and thus the successful design of a Naval Task Force as a warfighting system.

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1. C. M. Bennett, *A Naval Task Force Functional Performance Generation Methodology*, NCSC TM -545-90, Naval Coastal Systems Center, February 1991, UNCLASSIFIED.

2. "Hierarchy of Objectives: An Approach to Command and Control Warfare Requirements," SAI210605-047-0000, SAIC Comsystems Division, 10770 Wateridge Circle, San Diego, CA, 25 December 1989.

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